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# Reverberatory furnaces in the Puna of Jujuy, Argentina, during colonial times (from the end of the 16th to the beginning of the 19th century A.D.)

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ABSTRACT

This paper presents the study of the extractive metallurgical technology that was employed in four colonial mining-metallurgical sites in the high plateau (Puna) of Jujuy, Argentina, dedicated to silver exploitation during the 17th and 18th centuries. In these archaeological sites, we have identified the presence of reverberatory furnaces. We explore the development of this technology and show the results of the study of the furnaces found in the Puna of Jujuy, their functions and performance, based on our fieldwork and on the results of archaeometric analyses of smelting slag and vitrified clay samples. The excellent conservation of most of the furnaces makes them not only a great source of information for the study of colonial metallurgy in this region, but also a contribution to our understanding of mining and extractive metallurgy in the Andes, of the circulation of workers and technical knowledge and of the changes generated by the Spanish conquest.

## 1. Introduction

Silver mining has been pointed out as the engine of Andean economy during colonial times. Studies on the smelting technology employed in the benefit of these ores have especially focused on the description of the pre-Columbian furnace called *huayrachina*, reported by most of the Spanish chroniclers and employed almost exclusively for smelting silver minerals in the first phase of Potosí exploitation (1545–1571) (in present-day Bolivia), until the use of amalgamation (Bakewell, 1984, 1989; Timberlake, 2000; Salazar-Soler, 2002; Téreygeol and Castro, 2008). The most outstanding characteristic of this natural draft furnace was having walls pierced with many holes through which the wind oxygenated the burning charge (Van Buren and Mills, 2005). Less common are studies that "assess the variability of smelting technology that appears to have existed in the southern Andes" (Van Buren and Mills, 2005: 4), both before and during colonial times. As a contribution to this important issue, this paper aims to study the extractive metallurgical technology employed in four colonial mining-metallurgical sites dedicated to silver exploitation during colonial times (17th and 18th centuries) in the Puna of Jujuy, part of the southern extreme of the Andes High Plateau in the Northwest of present-day Argentina. The Puna of Jujuy is a rich area in ores of metalliferous minerals, such as gold, silver, copper and tin. Although these metalliferous resources were important to the inhabitants of this region, especially after the Spanish conquest at the end of 16th century, little is known, surprisingly, about how these ores were extracted and processed and what technology was used to smelt the silver-containing lead ores during colonial times. Unfortunately, colonial-period travelers and chroniclers largely ignored peripheral areas such as the Puna of Jujuy when documenting mining centers in the Andes. Before our work, no archaeological research focused on this issue had been conducted in the area.

In the four archaeological sites this paper analyzes, we have identified the presence of reverberatory furnaces, formed by three connected compartments (chimney, chamber and firebox) (Angiorama and Becerra, 2010). To date, the function and characteristics of reverberatory furnaces in the Andes are not well known because few are documented and published. The excellent state of conservation of most of the furnaces found in the sites we are presenting makes them a great source of information for the study of colonial metallurgy in this region.

Our paper shows the results of the archaeological study of these furnaces, their functions and their performance, based on our fieldwork and the results of archaeometric analyses of smelting slag and vitrified clay samples. It will also consider these furnaces in the light of the macro-regional colonial mining context, understanding that metallurgical technology, as any other, is constrained by physics, chemistry and geology, but also by historical settings, beliefs, prior choices, ideology, social organization (Killick, 2004) and the own skills and perception of the practitioner (Ingold, 2001). Which were the means and channels through which the reverberatory furnace technology

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spread and was chosen in different Andean mining centers during the colonial period? To try answering this question we consider the importance of the circulation of technical literature but especially, the migration of technicians, experimentation and oral transmission. As Van Valkenburgh et al. (2017: 18), we do not focus on the furnaces per se, "but on what they have to tell us about the processes of their production, circulation and reception". Moreover, we aim to contribute to the discussion on how they were incorporated into local mining traditions, considering it was not "a straightforward technology transfer" but "a more complex process of technological incorporation and emulation" (Van Valkenburgh et al., 2017: 18), related to the circulation of mining workers during colonial times.

## 2. Reverberatory furnaces

Ores are rocks, minerals or alluvial sediments that contain metals that are considerable valuable and that can be mined and processed with the technologies available at a certain time (Killick, 2014). The smelting process aims to separate metal (silver-lead alloy in this case) from slag (the waste product that result from the gangue of the ore's host rock and from added fluxes) (Hauptmann, 2014: 91). The cupellation is the refining process where this silver-lead alloy is heated to separate silver from lead. As we have mentioned, studies on smelting technology in reverberatory furnaces in the colonial Andes are not very common. Some examples are the work by Van Buren and Mills (2005) and the rest of their team in Porco-Potosí (Cohen et al., 2008, 2009; Van Buren and Cohen, 2010) and also by Téreygeol and Cruz (2012) for Santa Isabel, southern Lípez. These researchers analyzed the *tocochimbo*, a pre-Columbian round muffle furnace less than 1 m in diameter, employed for refining inside the indigenous houses (Barba [1640], 1939; Bargalló, 1955; Van Buren and Mills, 2005) and the reverberatory furnaces used for smelting and refining. In this paper we will focus on this latter type of furnace. Based on the description of Alonso Barba ([1640] 1939), other colonial documents and their own archaeological work, Van Buren and Mills (2005: 25) described the reverberatory furnaces as "a double-chambered furnace that is covered with an arched roof and has a chimney at one end. Ore is placed in the chamber closest to the chimney and is heated by the hot air produced in the fire chamber [firebox], from which it is separated by a low wall". This separation between ore and fuel is one of the distinctive characteristics of this technology, that isolates the material being processed from contact with the fuel, but not from contact with combustion gases (Fig. 1). On the contrary, in the huayrachina, ore and fuel are placed together, mixed, in a single compartment.

The term reverberation is used to denote the circulation of the flame from the top of the furnace back to the bottom (Nicholson, 1818), in a generic sense of rebounding or reflecting.

The chronological development of reverberatory furnace technology is not yet completely clear. There are references to this kind of technology in European manuscripts such as *De Re Metallica* by Georgius Agricola (1556, trans. 1950) or *De la Pyrotechnialibri X* by Vanoccio Biringuccio, (1530–1535) (see Cohen et al., 2009). However, they differ from the ones described for the colonial Andes. For example, the use of these furnaces in Europe seems to be only for refining and not for smelting. This is also the case of the ones recorded in the mining centers in New Spain (present-day Mexico) (see Sánchez Gómez, 1989: 505; Bakewell, 1997: 202). On the contrary, in the Southern Andes, this technology was used for both processes (smelting and refining), in the same or in a smaller furnace. Moreover, Lechtman et al.'s (2010), Cruz (2009) findings in Pulacayo, Bolivia, suggest that reverberatory furnace technology was also known and employed during pre-Columbian times in the Andes (Cruz and Téreygeol, 2014).

According to the work of Alonso Barba ([1640] 1939) 1640, reverberatory furnaces were used in many mining centers in Central and Southern Andes for smelting silver minerals, in tandem with amalgamation (method of silver extraction from ores based on the properties of mercury to alloy with silver). European and indigenous miners in the Andes would have invented new ways of using the furnaces brought from Europe or formerly known in the Andes, changing the original designs to adapt them to local conditions, mineralogy and other contexts of exploitation, certainly drawing on their previous experience. Diverse reverberatory furnaces were apparently used in the colonial Andes by indigenous miners, and also by individual European entrepreneurs, especially with little resources to invest or during shortages of mercury (Bakewell, 1984). However, as mentioned above, there are not many archaeological studies focused on this kind of furnace, their performance, place and time of use. Pfordte (1893, 1894), at the end of the 19th century A.D., described the use of these furnaces in Pasco, Perú, and in other regions of the country (Yauli, Bellavista en Chicla, Cerro de Pasco, Humanrauca Vinchos, Visco, Huayro-Cancha, Morococha, and Santo Domingo). More recently, Van Buren and Mills (2005), Cohen et al. (2008, 2009) and Van Buren and Cohen (2010) studied the evidence of reverberatory furnaces in the Porco-Potosí area (Bolivia), showing they were employed by indigenous people with legal or semi-legal access to rich mineral sources. Furnaces of this types have also been found and analyzed in Santa Isabel, Southern Lípez and Berenguela, Pacajes, Bolivia (Téreygeol and Cruz, 2012), potentially linked to indigenous labor. Rivera Casasnovas (2008) has also recorded at least one possible reverberatory furnace in the region of San Lucas Valley, Chuquisaca, also in Bolivia. Recent surveys in Santa Bárbara, in

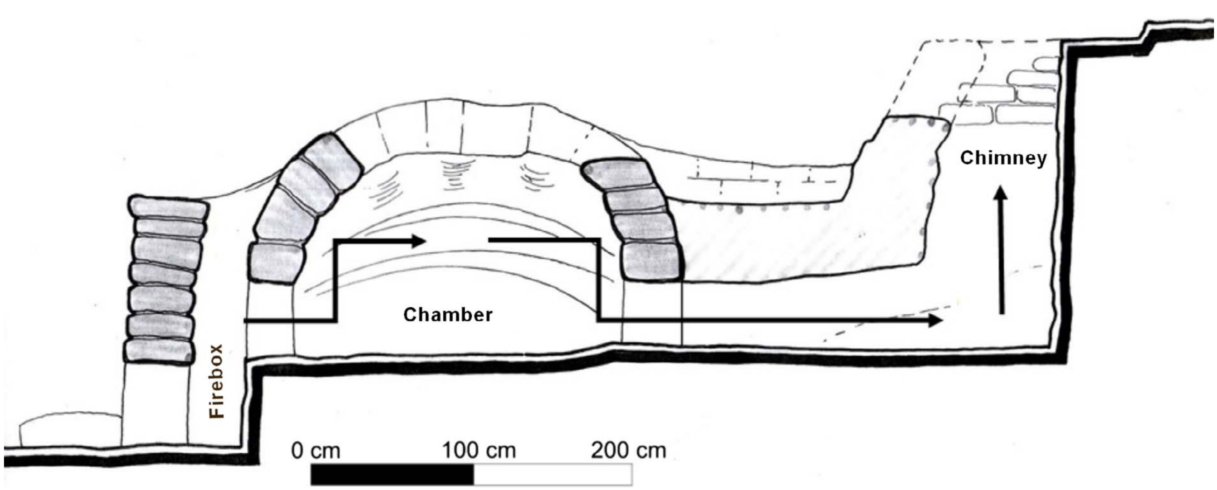


**Fig. 1.** Vertical section through a reverberatory furnace found in Fundiciones 2. Fuel is placed in the firebox, and its combustion gases reach the ores inside the chamber and leave the furnace through the chimney as indicated with arrows.


**Fig. 2.** A map of the archaeological mining-metallurgical sites mentioned in the text.

Northern Chile have identified similar furnaces there (Salazar, 2012, Personal Communication). The ones we describe in this paper are the first known in the Puna of Jujuy.

## 3. Puna of Jujuy: historical background

The Puna of Jujuy is a vast plain more than 3600 m above sea level where there are resources which have supported populations pursuing herding, agricultural activity and wild game hunting for the past 10,000 years. Moreover, there are certain resources specific to this area that became a major attraction such as salt, particular volcanic rocks, and ores of metalliferous minerals (gold, silver, copper and tin).

By the 15th century A.D., the Inka Empire conquered the region, remodeling previous sites, building new ones, investing in agriculture infrastructure and transforming the interregional traffic networks (Raffino, 1978; Albeck et al., 2007). During the last decades of the 16th century A.D. the Spanish conquerors were trying to ensure their dominion in the southern lands of the Inka Empire, the so called Ancient Tucuman (present-day Argentine Northwest). At the same time, the discovery of mines in the region later known as the Puna of Jujuy promoted the settlement of Europeans who were willing to search and work ores, hoping to find a mine so rich that it would compete with Potosí, the most important mining center in the Andes. In this context, administrative institutions and some ore-refining companies were established in the Puna, employing mainly indigenous people as manual labor force (Gil Montero, 2004; Palomeque, 2006; Sica and Ulloa, 2007; Becerra, 2012, 2014). Lands were distributed among Spanish conquerors (Albeck and Palomeque, 2009) and many towns were found near mining areas. Gold and, on a lesser scale, silver mining were prominent production activities during colonial times, not only as business enterprises managed by Spaniards but also, and mainly, as a source of funds for indigenous inhabitants. Unfortunately, we lack evidence of how pre-Columbian inhabitants of the Puna processed and smelted ores. In fact, the absence of clear evidence of mining and metallurgical practices from Late and Inka Period in the region led us to consider that these activities were not as relevant for the pre-Columbian population in this region of the Andes as they were during colonial times (Angiorama and Becerra, 2014). In this context, it is difficult to say whether Puna miners and smelters were familiar with reverberatory technology before the arrival of Europeans.

As in the rest of the Andes, mining activity provided indigenous population with the means to access foreign products and pay the compulsory tribute to the Spanish crown (Conti and Santamaría, 1994; Palomeque, 1994; Becerra, 2014). Moreover, mining activity indirectly facilitated the inclusion of indigenous groups in colonial commercial relationships. In this case, Puna herders were especially related to the extraction and commercialization of salt, the provision of foodstuffs and the transport of all kinds of products and goods associated with mining for local and non-local mines and mining villages (such as the ones within Charcas jurisdiction in present-day Bolivia, see Assadourian, 1982). These diverse activities were so successful in the Puna that at the end of the 18th century A.D. a significant population inhabited the region (Gil Montero, 2004; Sica and Ulloa, 2007). However, despite the desire of Spanish and indigenous inhabitants and workers, the Puna of Jujuy never became a new Potosí, and the scale of production was low compared to other mining areas in the north of the Puna. During the 17 and 18th centuries A.D., we have identified periods of time when there were investments and high expectations regarding the success of the mining enterprises, followed by periods of lack of formal or recorded activity. Mining projects in the Puna faced several difficulties: floods in the adits (nearly horizontal passage from the surface in a mine), lack of labor force, poor minerals, among others (Becerra, 2014).

## 4. The furnaces in the Puna of Jujuy

Since 2008, we have been carrying out extensive fieldwork in various mineral-rich areas of the Puna of Jujuy (Rinconada and Santa Catalina's department, Jujuy, Argentina). As a result of this investigation, four mining-metallurgical installations were found. Within these installations, reverberatory furnaces were built and used for smelting silver-containing lead ores probably in the 18th century A.D.: Fundiciones 1 and 2, Pan de Azúcar 1 and Casablanca (Fig. 2).

In **Fundiciones 1** there are four reverberatory furnaces. They are located near a lead-silver mine called Mina Chinchillas, which has been intermittently exploited with modern methods at least since the end of the 19th century. Four adits and a small abandoned mining camp are the evidences of these mining activities. However, it is most likely that this mine was also the source of the ores smelted during colonial times

**Fig. 3.** Fundiciones 1. (a and b) Furnace 1, formed by three connected compartments: firebox, chamber and chimney. This furnace is completely preserved. (c) Furnace 2. Only half of the chamber and the chimney are preserved. The channel connecting both compartments can be seen.

in the furnaces found in Fundiciones 1 and 2. This area is also very rich in alluvial gold, so a colonial town called Santo Domingo was found in the 18th century and several temporary shelters and some residential units were built by miners nearby.

Only one of the furnaces in Fundiciones 1 is fully preserved (Figs. 3a, b, and 4). That one and a second one (partially conserved, Fig. 3c) have respectively chambers of 2 and 3 m of external diameter, while the other two seem to be considerably smaller, according to the dimensions of the chimney and chamber foundations.

The fully preserved furnace is formed by:

– a prismatic firebox with two shelves made of plain rocks and five windows (one frontal, two lateral -one on each side-, one upper central and one very small and round in the front wall). These shelves were probably used to place the firewood. Neither the inside walls of the firebox nor the windows show evidence of vitrification (glassy substance made by heat and fusion of the original rock or clay components). However, signs of thermo-alteration (red and black spots) are observed in the upper and round windows. No slag was found inside this box.
– a chamber with a central round hole, a lateral window divided in two by a plain rock and on the opposite side of the lateral window, four small and round holes. A small excavation was conducted in the edge of the lateral window in order to identify any soil alterations produced by possible emptying of the furnace through this channel. However, no modification was detected. Inside the chamber, a portion of vitrified floor remains. The rest was probably removed to be melted again for recovering the metal. Another excavation showed that below this floor there is a 15 cm-thick, loose, gray sediment followed by a more compact, reddish and clay-rich deposit. The inside walls of the chamber are lined with heat-altered, crackled and metallic gray clay. The upper window shows a dark-colored heat alteration, while the small round holes display brownish, black and green vitrification.
– finally, a conical chimney, connected to the chamber through an underground channel roofed with plain rocks (maximum width 0.55 m and length 1.2 m). The chimney is only partially conserved and there are several collapsed rocks inside. The inner walls show green vitrification.

It should be noted that some of the rocks in the furnace show evidence of high-temperature exposure, not only on their inner surfaces but also on their outer surfaces. This fact leads us to believe that the furnace could have been re-built at least once.

We expect that the rest of the furnaces could have been very similar to this one, but smaller.

In **Fundiciones 2**, 2.5 km away from Fundiciones 1, there are 5 furnaces, two residential units and a deposit (Fig. 5). Nevertheless, no cultural material was found on the surface or in excavation.

The furnace design is quite similar to the found in Fundiciones 1. One of the five furnaces has a firebox with an upper and a frontal window, and a possible third window, on one of its sides

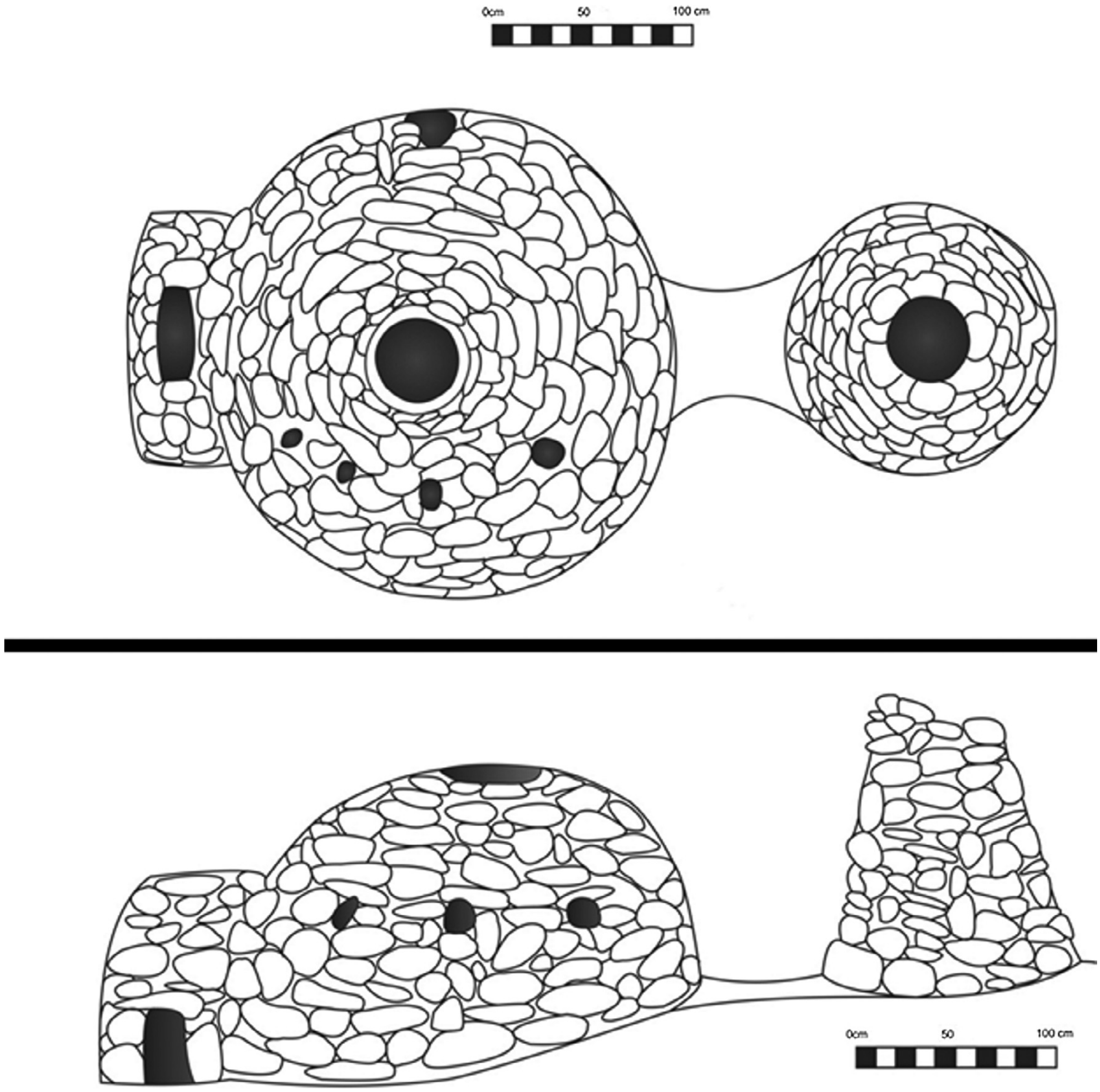


**Fig. 4.** Fundiciones 1. Furnace 1. Details of the furnace where the three compartments and the several windows and entries can be observed.

(Figs. 5d and 6a, 1). It does not have, however, the small hole described in Fundiciones 1's furnace. There is a broken rock in one of the walls, possibly part of a shelf. The vault chamber has three small round holes on its sides (less than 0.2 m in diameter) and a large window in the center (0.7 m in diameter). The chamber is partially collapsed, but we believe there could have been a window on one of the sides, such as in Fundiciones 1. The floor is also vitrified. The inner walls of the firebox are thermo-altered and show vitrification in many areas, especially near the connection between the chamber and the firebox. It seems that part of the liquid slag flowed from the chamber into the firebox during the smelting process, generating vitrified floor there, similar to the one found in the chamber.

Part of a dark vitrified floor remains inside the chamber. It shows an inclination towards the center of the furnace. An excavation conducted in a portion of this floor without vitrification indicates that there were at least two smelting events. The inner walls of the chamber are also lined with crackled and thermo-altered clay, showing dark, brown and green vitrification.

As in Fundiciones 1, the presence of thermo-alteration on the external surfaces of the rocks of which the furnace is composed indicates that it was built at least twice.

Fundiciones 2 has four more furnaces, which have some special characteristics. Three of these furnaces show the same design (firebox, chamber and chimney) but they were built inside a rectangular enclosure, specially prepared for them (Fig. 7). The enclosure is 14 m long and 3 m wide, with eleven points of entry, one for each firebox, and one for each chimney, plus five more that allowed people to move in and out. Due to the location of the chimneys, gas emissions could have occurred outside the building.

All the furnaces are almost completely buried, making it difficult to distinguish their windows or any evidence of thermo-alteration (Figs. 5a–c, and 6b). We have excavated the best preserved one: it has a rectangular firebox (without shelves or divisions), with one upper and one frontal window. The chamber has a central upper window, and two small holes, one on each side. The chimney is not well preserved. The chamber does not have a vitrified floor like the furnaces described before. Instead, it has a 20 cm-thick layer of white ash. In addition, the inner walls show yellow vitrification. No slag was found. In the firebox, there are no signs of vitrification nor any ash or charcoal.

The fifth furnace in Fundiciones 2 is located outside this building, and it is very small (Figs. 5e and 6c). The chamber is 80 cm in external diameter, and has two small windows, one on each side, plus the upper central hole. The firebox is rectangular but a rock divides it in two halves. An excavation was conducted inside this box, showing no signs

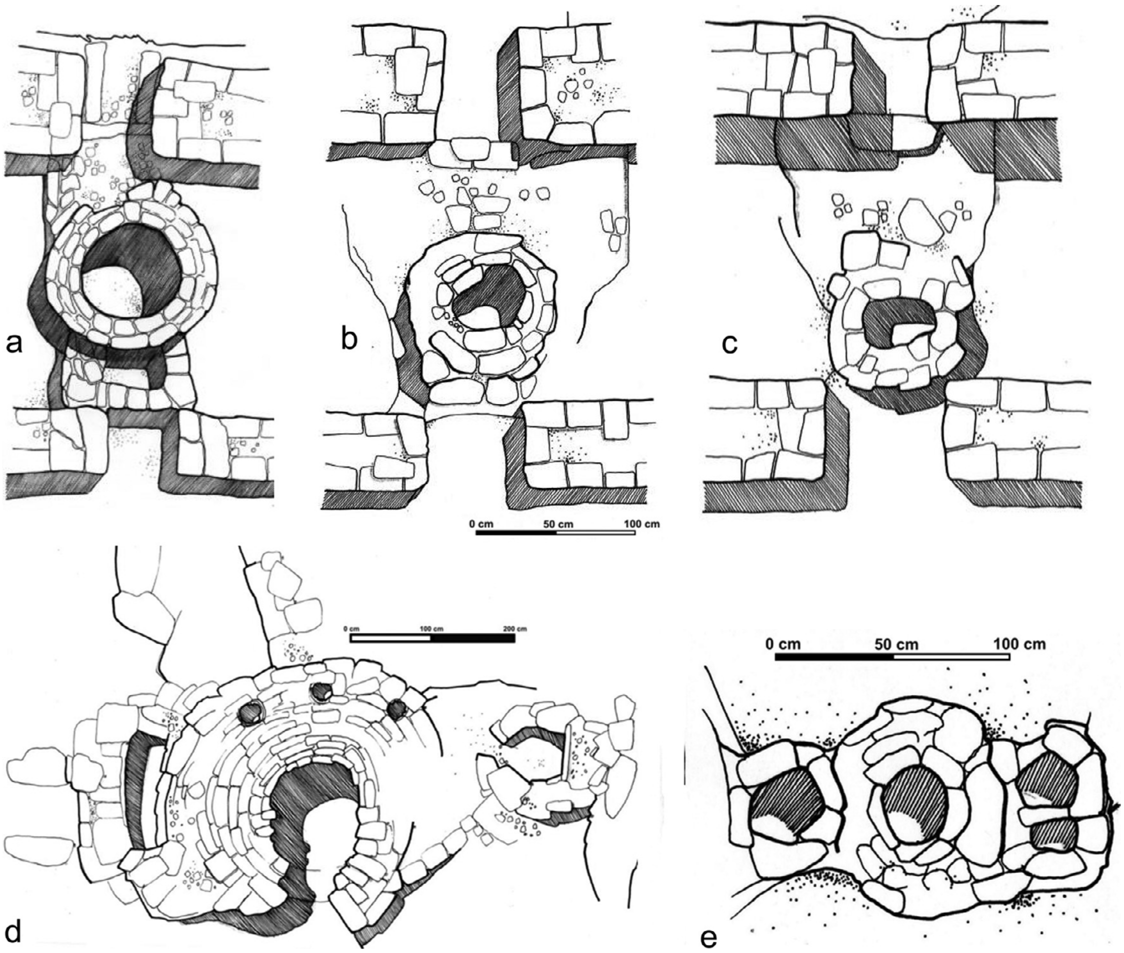


**Fig. 5.** Fundiciones 2. Drawings of the five furnaces found in this metallurgical installation. The first three were built inside a rectangular enclosure. The two more furnaces are outside this building. (a) Furnace 1. Firebox and chamber are preserved. (b–c) Furnace 2 and 3. Only the chambers are preserved. (d) Furnace 4. Although partially preserved, the firebox, chamber and chimney can be observed. The chamber has three small round holes. (e) Furnace 5. Smaller than the rest of the furnaces, it is completely preserved. The firebox is divided by a rock in two halves.

of vitrification, ashes or charcoal. On the contrary, and like the furnace excavated inside the building, the chamber has a thick layer of ashes, but in this case the walls do not present any vitrification at all and there is no slag.

Many rocks used for building the furnace belonged to previous furnaces and show vitrification on their external surfaces.

In **Pan de Azúcar** there is also a well-known silver-lead mine that was active until recent times. Although it is now abandoned, the Pan de Azúcar village is still inhabited by several families. Nearby, archaeological evidences of pre-Columbian and colonial occupation have been found (Angiorama et al., 2013, 2015). On a slope of a hill, we have identified a partially preserved furnace (Fig. 8). It has a 2 m in diameter chamber, and some walls are collapsed. Inside, fragments of dark vitrified floor and slags are found. The inner walls of the chamber, on the contrary, are not vitrified at all. There is a second lateral entry to the chamber, only identified from the inside because it is sealed by a rock. From the outside, there is a 1.4-meter-long line of thermo-altered rocks that could have formed a surface channel connected to the chamber through the now closed window. Only the foundations of the chimney and of a second 1.3-meter-long surface channel connecting it to the chamber are preserved.

The firebox is not preserved, but it can be inferred that there was one. Associated with this furnace, there are numerous slags, thermo-altered rocks and a few sherds without any decoration.

Finally, in **Casablanca**, we have registered three furnaces, at the bottom of a slope. Unlike the rest of the sites described so far, no silver mine is known in the area. In fact, gold mining was very important and lead during colonial times to the foundation of a town located 5 km from Casablanca: Rosario de Coyahuayma. Evidences of gold mining there can be traced back to Inca occupation (Angiorama and Becerra, 2010).

The furnaces in Casablanca are partially buried so we based our descriptions on the one that is the best preserved (Fig. 9). The chamber has an external diameter of 2.5 m. It has three small holes, a lateral square window and a central upper hole. There is a 1.2-meter-long underground channel that can only be seen from the inside of the chamber. There is also a second channel connecting the chamber to the chimney, partially preserved. This channel is on the surface and it was built with plain rocks. The firebox is not preserved and the chamber wall that was connected to it has collapsed.

The inner walls of the chamber and chimney are covered by a white and yellow layer, evidence of high temperature exposure. On the contrary, in the collapsed sector, there is a big rock with green vitrification.

According to the descriptions above, we can infer the use of two types of reverberatory furnaces in this region: the ones found in Fundiciones 1 and 2, and the ones registered in Pan de Azúcar and Casablanca. They differ because the latter ones have an extra channel coming out the chamber (not only the one conducting to the chimney as in the first type) and only an inferred firebox (not preserved in any of the four furnaces).

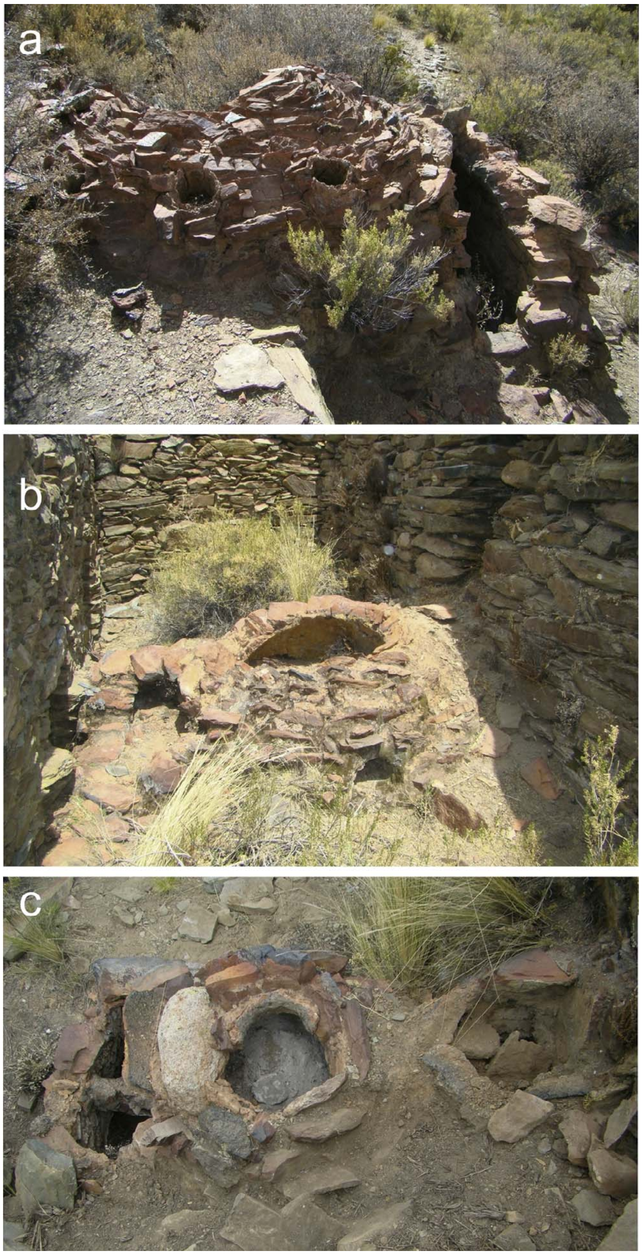


**Fig. 6.** Fundiciones 2. (a) Furnace 4. Chamber with round holes and firebox. (b) Furnace 1. Located inside the building, one of the small holes in each side can be seen in the picture. (c) Furnace 5. Divided firebox, chamber and chimney. In the chamber, a thick layer of ashes can be observed.

## 5. Slag analyses

Unfortunately, we have not found tools, metals or any diagnostic cultural material in any of the four sites. Only slag is omnipresent, so we have analyzed 72 samples associated with the reverberatory furnaces at the four sites. To do so, we have observed and analyzed polished slag surfaces using optical microscopy, scanning electronic microscopy (SEM), electron probe micro-analyzer (EPMA), and chemical micro-analysis techniques (EDS and WDS). No matter the furnace designs the slag are associated with, or the macroscopic differences among the slags, all the examined samples are quite similar in composition and can be compared with the samples analyzed by Cohen et al. (2009) from Porco's reverberatory furnaces in present-day Bolivia. They are products of the extractive metallurgy of lead sulphide minerals with silver content (argentiferous galena) and they have a glassy matrix rich in lead: between 18 to 35%w silica ($SiO_2$), 4 to 6.75%w alumina ($Al_3O_2$) and 35 to 70%w lead (PbO).

Inside the matrices, metallic and non-metallic phases are detected. The former include prills (spherical pellets) of lead sulphides (on average 14%w sulphur and 66%w lead) (Table 1) and also lead oxides with silver, copper and/or antimony. The latter are generally oxides of calcium (probably wollastonite) and phosphorous (Becerra et al., 2014) (Fig. 10).

In general, the sulphur content is quite low in all the samples, except in the ones from Casablanca and Fundiciones 2, where lead sulphide prills are more common. They were formed by the melting and recrystallization of galena, indicating a lower efficiency in the smelting processes carried out at both sites, in comparison with Pan de Azúcar or Fundiciones 1, where it is less common to detect lead sulphides in the slag. In the first two cases, the sulphur was not completely released as sulphur dioxide to the atmosphere, as it should have occurred in optimal conditions. In any case, the low content of silver in all the analyzed samples indicates that the main goal of the process, which was obtaining a silver-lead alloy to be refined later, was consistently achieved, although sulphides are still present in some of the slag samples.

## 6. Furnace use

According to the characteristics of the furnaces found and the results of the slag analyses recovered in the sites of the Puna, at least the best preserved furnaces in Fundiciones 1 and Casablanca, the big outdoor furnace in Fundiciones 2 and the one in Pan de Azúcar were employed for extractive metallurgy of silver-containing lead ores. Fuel was placed on the shelfs of the firebox and its combustion gases reached the ores inside the chamber and left the furnace through the chimney. When the ore was completely smelted, the metal and slag would be separately removed from the furnace. There were two methods (Alonso Barba [1640], 1939; Cobo in Jiménez de la Espada, comp., 1885: CL): the liquid metal could flow in a channel or the smelters could simply wait until the furnace and metal were cold and then break the slag in the surface to recover the lead-silver alloy. Although in the Puna of Jujuy there are two different designs used for the reverberatory furnaces, the ore smelting processes were carried out quite successfully in all the furnaces, even though lead sulphide is still present in Casablanca and Fundiciones 2's samples. Unfortunately, at the time we cannot explain the function of the extra channel coming out the chamber observed in Casablanca and Pan de Azúcar's furnaces or the divided firebox present in the small outdoor furnace in Fundiciones 2. It is clear, however, that this last furnace and the three located inside the building in this installation, as well as the two smaller and not well preserved furnaces in Fundiciones 1, were probably used for refining to obtain pure silver prills. No slag was recovered from any of these furnaces. Only the size, color of the vitrified walls (where they can be observed), the presence of ashes in the chamber and, in the case of Fundiciones 2, the location of these furnaces inside a special building, distinguish them from the others. Based on the well-known work of Alonso Barba ([1640] 1939) about mining and metallurgy in colonial times, as well as on other chronicles and contemporary documents (Cobo, 1653 in Jiménez de la Espada, comp., 1885; Toledo 1569–1574 trans., 1986), we can infer that these furnaces were used for refining. According to these written sources, silver cupellation was carried out in small reverberatory furnaces and most of the time they were built inside indigenous households. The floors of the chambers were covered with a mixture of ashes and clay, where small holes or cups were made to place the silver-lead alloy. When heat it, this preparation would have absorbed the lead, purifying the silver. Regarding the material evidence of this process, Alonso Barba stated that the ashes and the walls of the chamber would become yellow if they had absorbed only lead. In case the charge still had silver, the color would be dark green. Such is the case of the furnaces in Fundiciones 2.

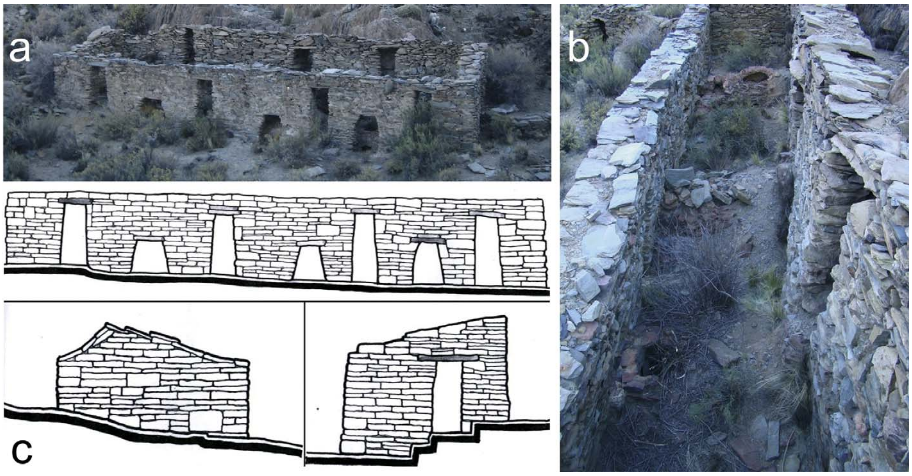


**Fig. 7.** Fundiciones 2. (a) Rectangular enclosure, specially prepared for furnaces 1, 2 and 3. Ten of the eleven points of entry can be seen (one for each firebox, and one for each chimney, plus five more that allowed people to move in and out). (b) Furnace 1, 2 and 3 inside the rectangular enclosure. (c) Details of front and lateral walls of the rectangular enclosure.

## 7. Furnace chronology

One of the most intriguing questions about these furnaces is when they were built and employed. Because there is no cultural material associated with the furnaces that could yield information about the chronology of the sites, we relied on written sources to propose hypotheses about the chronology of construction. As we have mentioned before, this kind of furnace was employed in different areas of the Andes, especially from the beginning of the 17th century A.D. to the 19th century A.D. In the case of the Puna of Jujuy, comprehensive documentary research shows that Casablanca, Fundiciones 1 and Fundiciones 2 are located outside the main area of mining exploitation during the first period of European occupation in the Puna region (first half of the 17th century A.D.). In fact, they are located on the lands of those who invested in mining during the last quarter of the 18th century A.D. who employed indigenous workers from different regions, as it will be explained later. Based on this, we propose that these three installations date from this later period (Becerra, 2014). The chronology of the furnace in Pan de Azúcar is even more difficult to determine, because it is located near a silver-lead mine that was exploited during almost all of the colonial period and until recent times. The small scale of work (one isolated furnace) indicates that it could be related to the labor of someone who, individually or in a small group, was dedicated to smelting silver-containing lead ores from the nearby mine (through extraction or recollection of the abandoned ores in the tailings left from previous exploitations). We should consider that Europeans and indigenous miners may have participated in this activity as a complement to other economic activities at any time during the colonial period.

## 8. Interpreting the use of reverberatory furnaces in the Puna and the macro-regional context

Based on the results of our intensive research on the Puna of Jujuy and the fieldwork at each mining and metallurgical installation located there, it is possible to state that during colonial times there was a predominance of smelting compared with mercury amalgamation for processing silver minerals. The richness of the silver-containing lead ores available in this region and the difficulty in obtaining mercury would have made smelting a more profitable way of processing ores for the Puna miners, no matter if they were European or indigenous.

It is important to highlight that this trend in silver-containing lead ores processing would not have been uncovered if we only relied on written sources, which mainly mention the presence or construction of at least four refineries known as *ingenios* in the area and the demand of mercury by the local miners, leaving only a few and undetailed allusions to the use of furnaces for extractive metallurgy. This silence could

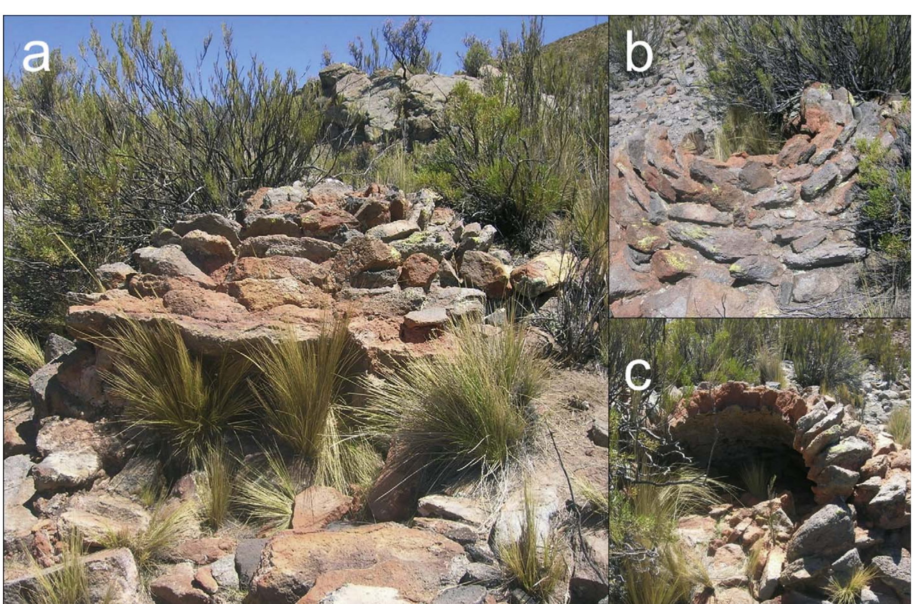


**Fig. 8.** Furnace in Pan de Azúcar 26. Details of the partially preserved chamber, (a) front, (b) back and (c) side view.

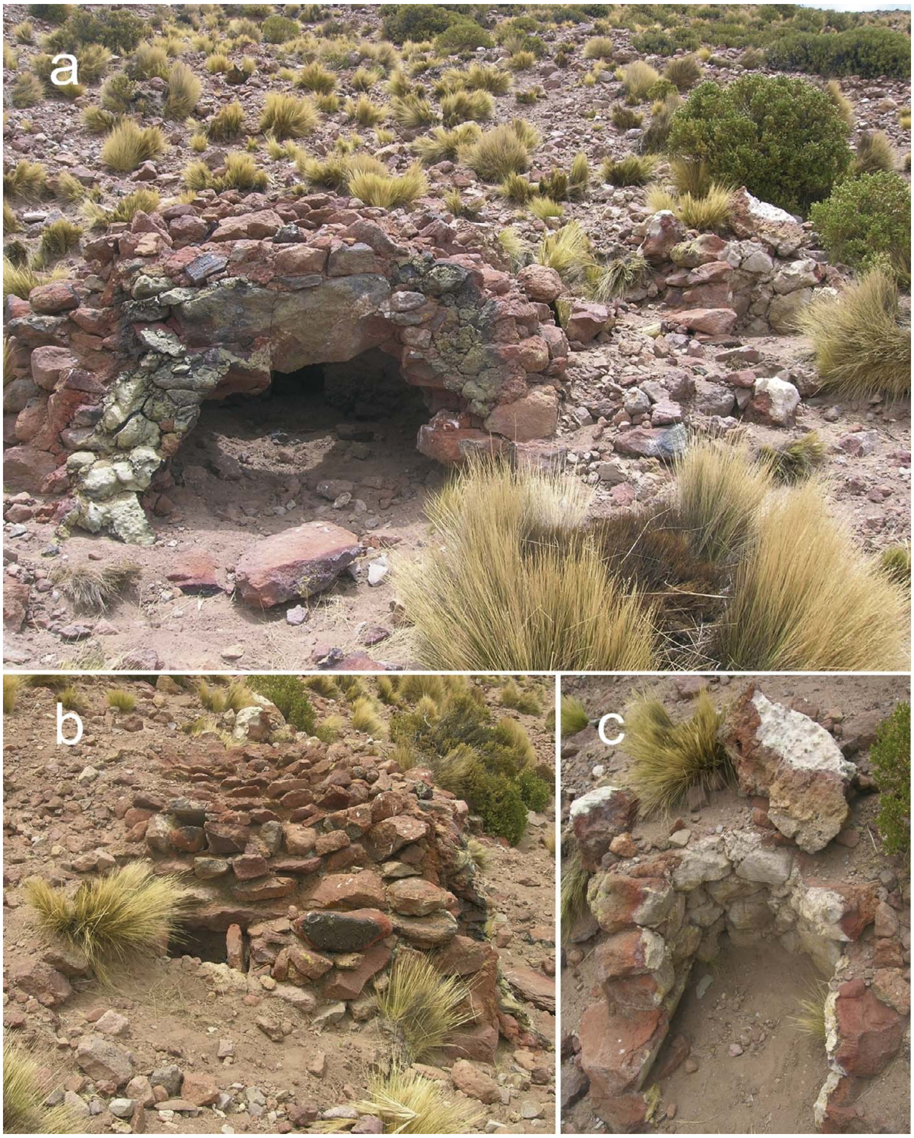


**Fig. 9.** Casablanca. Furnace 1. (a) Details of the partially preserved chamber with green vitrification in the collapsed sector. (b) Chamber lateral square window. (c) White and yellow layer covering the partially preserved chimney. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Composition of the metallic prills present in slag samples from Fundiciones 2, Fundiciones 1 and Casablanca (%w).

| Sample | S | Pb | As | Sn | Si | Cu | Zn | Ag | Sb | Fe | Al | K | Cl | Ca |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F2-1[a] | 13.98 | 84.41 | 0 | 0 | 0 | 2.49 | 0 | 0.08 | 0 | 0 | 0 | 0 | 0 | 0 |
| F2-1[a] | 13.94 | 83.42 | 0 | 0.02 | 0 | 4.47 | 0 | 0.07 | 0.06 | 0.05 | 0 | 0 | 0 | 0 |
| F2-3[a] | 13.52 | 84.16 | 0 | 0 | 0 | 1.38 | 0 | 0.34 | 0 | 0 | 0.01 | 0 | 0 | 0 |
| F2-3[a] | 13.23 | 85.28 | 0 | 0 | 0 | 1.17 | 0.04 | 0.24 | 0 | 0.01 | 0 | 0 | 0 | 0 |
| F2-3[a] | 13.85 | 81.81 | 0 | 0 | 0.01 | 5.57 | 0.08 | 0.34 | 0 | 0 | 0 | 0 | 0 | 0 |
| F2-5[a] | 13.28 | 84.51 | 0.03 | 0 | 0 | 0.66 | 0 | 0 | 0.02 | 0 | 0.01 | 0 | 0 | 0 |
| F2-5[a] | 12.94 | 85.22 | 0.02 | 0.03 | 0 | 0.60 | 0 | 0.02 | 0.03 | 0 | 0 | 0 | 0 | 0 |
| F2-5[a] | 13.29 | 85.29 | 0 | 0 | 0 | 0.43 | 0 | 0 | 0 | 0.04 | 0 | 0 | 0 | 0 |
| F2-9[a] | 13.41 | 86.98 | 0.05 | 0 | 0.01 | 0.74 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F2-9[a] | 13.78 | 85.86 | 0 | 0 | 0 | 1.25 | 0.09 | 0.05 | 0 | 0 | 0.01 | 0 | 0 | 0 |
| F2-9[a] | 13.73 | 80.10 | 0 | 0 | 0 | 4.88 | 0.02 | 0.06 | 0.03 | 0 | 0 | 0 | 0 | 0 |
| F2-10 | 13.55 | 88.25 | 0 | 0 | 0.01 | 0.54 | 0 | 0.11 | 0 | 0 | 0 | 0 | 0 | 0 |
| F2-37 | 5.97 | 60.50 | 0 | 0.02 | 0.01 | 1.24 | 0 | 0.08 | 0 | 0.40 | 0 | 0 | 0 | 0 |
| F2-37 | 6.13 | 60.38 | 0 | 0.09 | 0.04 | 1.22 | 0 | 0.22 | 0 | 0.35 | 0 | 0 | 0 | 0 |
| F1-3 | 15.15 | 53.66 | 19.78 | 0 | 0.87 | 3.38 | 0 | 0.67 | 0.30 | 0 | 1.10 | 0 | 0 | 0.18 |
| CB-8 | 22.20 | 75.20 | 0 | 0 | 0 | 0 | 0 | 1.76 | 0 | 0 | 0.14 | 0 | 0.27 | 0 |
| CB-8 | 23.80 | 0.38 | 0 | 0 | 0 | 73.30 | 0 | 1.78 | 0 | | 0.75 | 0 | 0 | 0 |
| CB-8 | 16.00 | 0.54 | 0 | 0 | 12.30 | 63.80 | 0 | 1.18 | 0 | 2.19 | 2.21 | 0.40 | 0 | 0.33 |
| CB-10 | 26.30 | 0 | 0 | 0 | 0 | 0 | 0 | 45.60 | 0 | 0 | 0 | 0 | 28.10 | 0 |

[a] Samples from Fundiciones 2 were analyzed with electron probe micro-analyzer and wavelength-dispersive spectroscopy (EPMA-WDS) while the rest were analyzed with scanning electronic microscopy and energy dispersive X-ray spectroscopy (SEM-EDS).

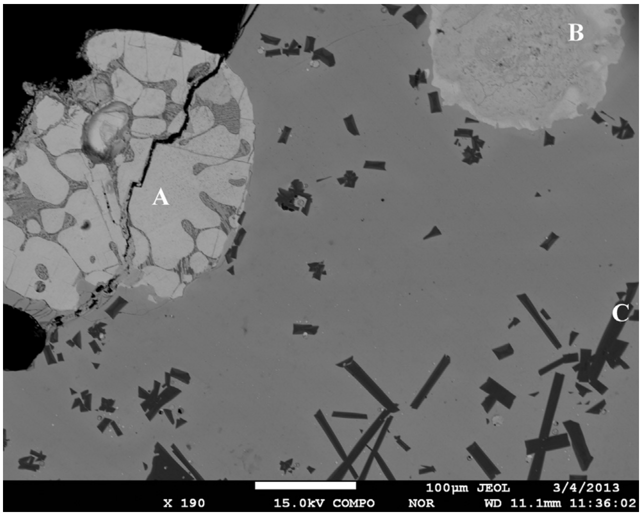


**Fig. 10.** Slag structure of a sample from Fundiciones 2 at 190× (SEM). (A) Prill of lead sulphides. (B) Prill of lead oxides with silver and copper. (C) Non-metallic phases.

be explained by the fact that smelting practices could avoid the payment of taxes and royal control. In fact, although some local documents mention the need to pay the royalty (the *quinto real*) we have not found any evidence that the local miners actually paid that tax (Becerra, 2014).

Another remarkable finding is that this type of furnace was employed in this area, peripheral to the major colonial mining centers in the Andes. The similarity of these furnaces is impressive, no matter the time of their construction nor if the mining installation was in the center of the mining area in Charcas -such as Porco, near Potosí, present-day Bolivia- (see Cohen et al., 2008, 2009; Van Buren and Cohen, 2010), in an important but secondary mining area -such as Santa Isabel, Lípez, also in Bolivia- (see Téreygeol and Cruz, 2012) or in the marginal area of the Puna of Jujuy, such as the ones described in this paper. This fact gives way to a number of questions, especially related to the movement of workers and the spread of technical knowledge between mining areas. If we consider the means and channels through which mining and metallurgical know-hows spread and were learned since the invention of the printing press, we must highlight the importance of the edition and circulation of technical literature, like the already mentioned books written by Biringuccio and Agricola on mining and ore processing. For example, we know that at least Agricola's work was read by people like the priest Alonso Barba, who made several references to this European treatise in his own work, *El Arte de los Metales*. The latter enjoyed great popularity among Andean miners and workers and also among painters due to his references to all kinds of minerals and pigments (Siracusano, 2008). We do not know if the Puna inhabitants actually read Alonso Barba's book, but according to the inventories found in historical archives, some Europeans living in the region owned texts related to mining and metallurgy (Judiciary Archives of Jujuy –JAJ-, Folder 33, File 1083, Year 1733, p. 20; JAJ, Folder 33, File 1091, Year 1731, p. 5overleaf, 15overleaf).

However, the most common way of disseminating new techniques and innovations continued to be the migration of technicians, experimentation and oral transmission. Through practice, perception and action (Ingold, 2001), workers and smelters of the mining centers familiarized themselves with new technical gestures that quickly became automatic to them (Latour, 2013). Potosí, as the most important mining area in the Andes, was the scenario of the daily encounter between European and indigenous miners and workers and their beliefs, technical knowledge and practices (Salazar-Soler, 2002). In that sense, it became a sort of academia of specialists who then traveled and worked in other developing mining areas. Gil Montero (2011), in her study of the San Antonio del Nuevo Mundo settlement, in Lípez, Bolivia, highlights the great mobility of workers who arrive from mining centers in the north of San Antonio, probably with previous training in Potosi's school. This also could be the case of the Puna of Jujuy. According to historical documents, the local indigenous inhabitants of this region were employed in mining activities in the Puna and also in Potosí, Lípez and Chichas mines, in present-day Bolivia. They were not included in the *mita* system, a colonial Andean system of rotating forced Indian labor organized mainly to work in the Potosí's mines. However, some of the *encomenderos* (Spaniards who had the right to collect tribute from the indigenous population), local landowners or businessmen forced them to travel and work in far and not so far mining areas, as well as in local enterprises (National General Archive –GNA-, Argentina, Sala XIII, Diverse Documents, Colonial Section, File. 11, p. 77; Provincial Historical Archive of Jujuy -PHAJ-, CMVT, Box 8, Folder 256, Year 1654; Madrazo, 1982; Zanolli, 1995). Moreover, around 1650 there were indigenous workers of unknown origins, probably Chicha or from other near mining areas, surveying and working mines in the Puna for themselves or hired by local and non-local European miners to undertake these activities on their behalf (National Archive and Library of Bolivia, -NALB- Mines 62-4, Year 1657). Their relationship with local indigenes is still unknown, although it has been said that it is probable that at least some of them were previous Puna inhabitants that remained outside the *encomienda* system (in the Puna or in the Chicha area) (Gil Montero et al., 2017). A century later, Bourbon authorities included a great number of *forasteros* (outsiders who paid tribute to the Spanish crown and not to any encomendero), some of which could have arrived to the Puna searching for ores or working in mining companies in the region. They rented lands or inhabited Puna towns, some of them only active due to their location near gold mines (Palomeque, 1994; Gil Montero, 2004; Becerra, 2014). They probably had previous mining experience acquired in other centers. Records show, for example, that a miner of the Puna hired workers from Potosí to carry out tasks that required specialized skills (NGA, Room IX, 36-2-5, Year 1802). These specialized migrants may have collaborated in disseminating new ideas, innovations and technologies, applying them according to local ores and mines, to other available resources (such as fuel sources) and to their own skills. Several researchers have pointed out the existence of pendular or cyclic circulation dynamics between indigenous communities and mining areas of colonial Andes (González Casasnovas, 2000; Gil Montero, 2011; Cruz and Téreygeol, 2014). These workers intermittently moved from one mining area to another one, or from their villages to the mines. This flux of people did not imply in most of the cases a breakdown of the worker's community ties, as it was understood originally (see Sánchez Albornoz, 1978). On the contrary, it entails community strategies to obtain the resources to pay the compulsory tributes (Saignes, 1987; González Casasnovas, 2000; Gil Montero, 2011). It is quite interesting that these indigenous communities or mining areas of Charcas (south of present-day Bolivia) are the places where some of the afore-mentioned *forasteros* in the Puna of Jujuy came from (Estarca, Oruro, Esmoraca, Chocaya, for example. See Rojas, 1913; NGA, Room XIII, 17-2-1, Years 1785–1792). These data suggest the inclusion of the Puna into these great circuits or into similar ones. In this context, the furnaces are indices of this circulation and of the changes generated by the Spanish conquest and by the development of mining on a large scale.

## 9. Final words

Just a few decades ago our knowledge about pre-Columbian and colonial ore processing technology was mainly limited to descriptions made by European chroniclers about how indigenous miners smelted silver ores in *huayrachinas* or applied amalgamation to extract metals. As we mentioned, recent archaeological and archaeometrics studies have revealed a greater variety of technologies applied, transformed and transmitted by European and indigenous peoples from different regions and times. Our paper is a contribution to these studies, directing our attention to a peripheral and poorly known mining area: the Puna of Jujuy in present-day Argentinean Northwest. Many questions, however, remain unanswered. One of them is why we found so little diversity in the furnaces used in the Puna of Jujuy. One possible reason is that reverberatory furnaces were very efficient and adequate to benefit the local lead-silver minerals, while most people were dedicated to gold mining, an industry which required less investment and part-time dedication. Although recent researches have shown the use of these furnaces in several places in the Andes, much more information is needed for further interpretations. This is a first step in that direction.

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